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## Initial conditions for massive star formation

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**Abstract.** In this contribution, our knowledge of the initial conditions under which massive star formation takes place is reviewed. Massive stars are born in massive clumps of giant molecular clouds (GMCs), hence first the properties of GMCs are summarized. As a potentially early stage of molecular clouds, infrared dark clouds have been discovered a decade ago as dark patches in mid-infrared (MIR) images of the Galactic plane and many studies of the physical conditions within them have been conducted recently. Without the guidance of MIR absorption, large scale, unbiased cold dust surveys can be used as well to identify massive cold clumps. In the absence of indicators of ongoing massive star formation, like compact HII regions and bright IR sources, these clumps are the most promising objects for the study of the initial conditions of massive star formation. Current observational approaches to find IR quiet clumps and their physical and chemical properties are summarized.

### 1. Introduction

In the last decade, much progress has been made towards understanding of the earliest phases of massive star formation. While in the nineties most studies of early stages targeted hot objects, namely compact HII regions and hot molecular cores (e.g. Kurtz et al. 2000; Churchwell 2002), we learned only in indirect ways, for example through chemical properties, about their initial conditions. Time was ripe then for advances in the field of also colder stages with the advent of new IR mission, mm/submm bolometer arrays and clever molecular line observing strategies. Previously, the initial conditions of massive star formation were covered in depths in the reviews by Evans et al. (2002), Menten et al. (2005), and Beuther et al. (2007), but many new studies were published in the field during the last two years, justifying a further summary of recent results.

An instructive example is given in Fig. 1., showing a zoom into our Milky Way at a Galactic longitude of  $30^\circ$ : Massive star forming regions are among the brightest objects seen in mid-/far- infrared surveys of the Milky Way. They are distributed along the Galactic plane with a scale height of only  $\sim 100$  pc. Large scale molecular surveys (e.g. the Galactic Ring Survey, Jackson et al. 2006) show giant molecular clouds (GMCs) with sizes of tens of parsecs as the birth places of massive star forming regions. Submillimeter dust observations of such clouds (e.g. from the SCAMPS survey, Thompson et al. 2005) reveal parsec-scale dense clumps embedded within the GMCs as the local environments for different stages of massive star formation, from relatively late stages like (ultra)compact HII regions (UCHIIs) to the supposedly earliest stage of massive cold clumps. An interferometric view of such a region in the cold and dense gas tracer  $\text{NH}_2\text{D}$  is

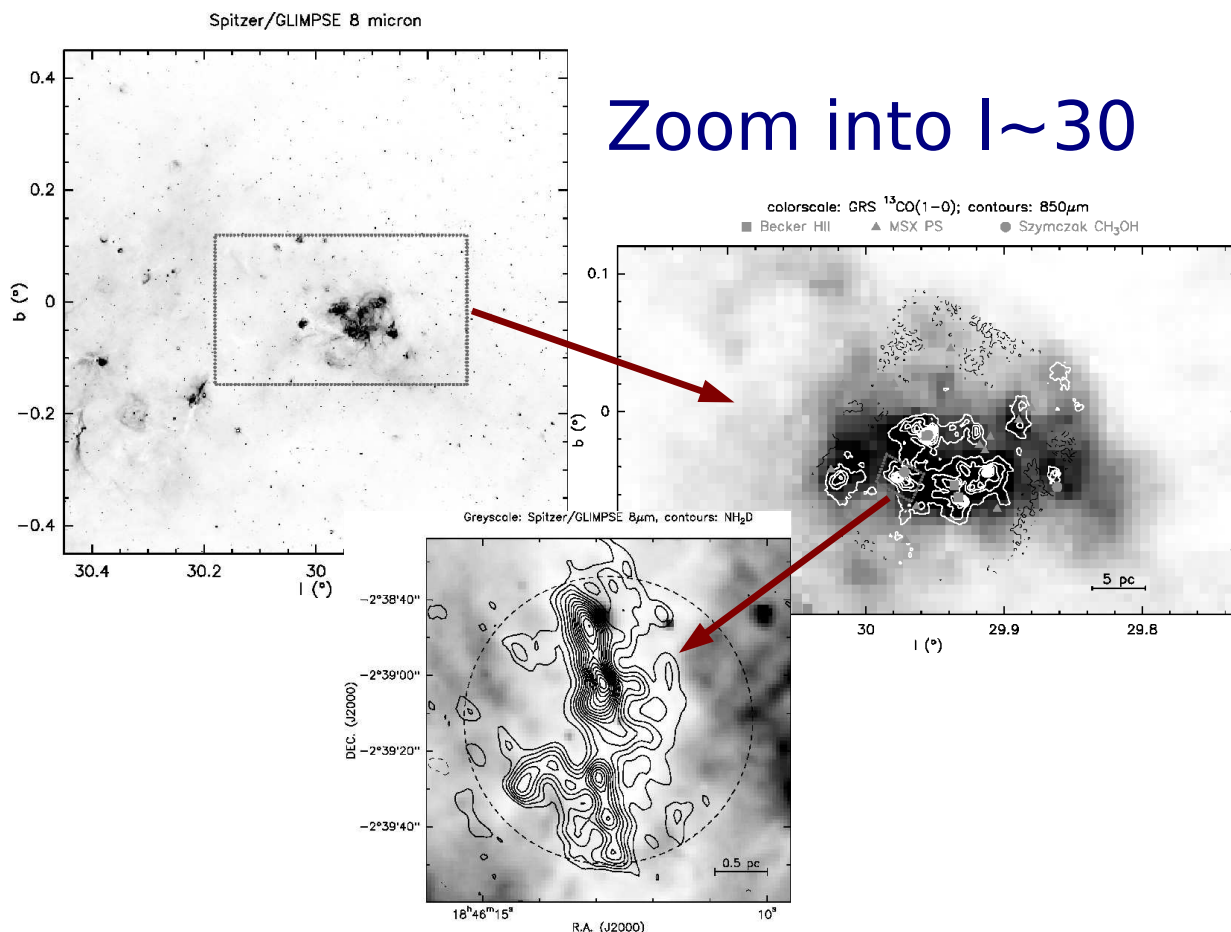


Figure 1. Upper left: Spitzer/GLIMPSE 8  $\mu\text{m}$  emission of the Galactic plane. Upper right: Overlay of submm dust continuum (Thompson et al. 2005) in contours onto  $^{13}\text{CO}$  from the Galactic ring survey (Jackson et al. 2006). Lower left: Overlay of  $\text{NH}_2\text{D}$  contours (Pillai 2006) onto GLIMPSE 8  $\mu\text{m}$ .

seen in the lower part of Fig. 1., where the clump breaks up into several highly deuterated 0.1 pc cores, many of them seen in absorption in the mid-infrared.

This review will mainly cover the observational side of the initial stages of massive star formation and focus on “cold” stages before infrared-bright massive young stellar objects, hot molecular cores and UCHII regions form. It is divided into 4 main parts: In section 2. the large environment will be described, section 3. gives an overview of current searches for the earliest stages of massive star formation, section 4. discusses the current knowledge of the properties of the found clumps, and section 5. deals with the small scale view of those clumps.

## 2. Large scale environs

### 2.1. Giant molecular clouds

From large scale CO surveys (e.g. Heyer et al. 1998; Dame et al. 2001; Jackson et al. 2006) we know that massive stars form in giant molecular clouds. These clouds have diameters of 10–100 pc, masses of  $\sim 10^{5-6.5} M_{\odot}$ , mean densities of several  $100 \text{ cm}^{-3}$  but they are strongly clumped (e.g. Stutzki & Guesten 1990).

For the substructures in the clouds, different terminologies exists. In what follows the nomenclature suggested by Williams et al. (2000) will be used. The condensations seen in the dust continuum map in Fig. 1. are called clumps. In molecular line maps, they are coherent, overdense structures in l-b-v, which might form whole clusters. At the distances to the bulk of the massive star forming regions, at several kpc, they are typical single dish mm-telescope targets.

Substructures within the clumps are cores. They might form individual stars or multiple systems and for typical distances, interferometers are needed to resolve them.

Currently there are two competing views on the physical state of GMCs, which in this contribution can only be discussed briefly. The first one sees GMCs as dynamic, transient objects (e.g. Ballesteros-Paredes et al. 2007). The clouds formed by large scale colliding gas flows and have lifetimes of about the dynamical crossing time. The second interpretation considers GMCs as quasi-equilibrium self-gravitating objects (McKee 1999) with lifetimes of many crossing times. See e.g. McKee & Ostriker (2007) for more details.

How can we identify the cold and dense parts of GMCs which might lead us to the initial stages for massive star formation?

### 2.2. Infrared dark clouds

In the late nineties, so-called infrared dark clouds (IRDCs) were recognized as potential sites for cold precursor stages of MSF. They were discovered in large scale mid-infrared surveys of the Milky Way conducted with space telescopes: Perault et al. (1996) reported “numerous dark features” in the ISOGAL survey and Egan et al. (1998) a “population of dark cores” observed in the MSX survey. Those features are due to absorption of the bright, diffuse MIR emission of the Galactic plane by cold, high column density clouds ( $A_V > 25$ ). Detailed reviews of their properties can be found in Menten et al. (2005) and also in Jackson (this volume). Menten et al. (2005) discusses the remarkable resemblance in dust continuum maps of IRDC G11.11 and the Orion molecular cloud. Hence, there are large IRDCs that resemble the high column density parts of GMCs, but there is also a large population of smaller clouds, down to “IR dark clumps”. Whether clouds show up as IRDCs depends strongly on the MIR background and the evolutionary state and geometry of the GMCs. That the clouds indeed show large column densities of cold molecular material was shown with  $\text{H}_2\text{CO}$  and  $\text{NH}_3$  observations by Carey et al. (1998) and Pillai et al. (2006a), respectively.

### 3. Searching for initial stages of MSF

In the pre-IRAS era, most of young massive star forming regions were found by their association with compact HII regions and maser emission (e.g. Churchwell 1990). With the help of the results from the IRAS satellite, Wood & Churchwell (1989) were able to develop IRAS color selection criteria for ultracompact HII regions (UCHIIs) which paved the way for systematic studies of UCHIIs, their environments and also their precursors (see next subsection). From the galaxy-wide statistics of UCHII regions and massive stars, Wood & Churchwell (1989) derived a lifetime of  $10^5$  years for the UCHII stage, much longer than what is expected from the expansion of a Strömgren sphere. Possible solutions to this “lifetime problem” are discussed in e.g. Churchwell (2002). In molecular line follow up studies, many hot molecular cores were found associated with the UCHIIs, which mark a stage before the occurrence of an UCHII, that might still be quenched by ongoing accretion (Walmsley 1995). Most of the hot cores are also associated with maser emission. Another complementary IRAS color approach was followed by Henning et al. (1990) to select candidates for so-called BN-type objects.

#### 3.1. Maser selected surveys

Water and methanol masers might trace young stellar objects (YSOs)  $< 10^5$  years,  $\text{CH}_3\text{OH}$  maser in particular probing only massive YSOs, hence they can be used as search beacons for early phases of massive star formation. This was done systematically by Walsh et al. (1997, 1998, 2003) with surveys for  $\text{CH}_3\text{OH}$  masers of objects with IRAS colors resembling UCHII regions and subsequent follow up programs. An unbiased approach was taken by Szymczak et al. (2002) with their survey for methanol masers over 20 square degrees of the northern Galactic plane. A much deeper blind survey was carried out by Pandian et al. (2007). The most complete approach in this respect is the currently ongoing methanol maser survey of the whole Galactic plane (Cohen et al. 2007). Plume et al. (1997) studied in detail the physical conditions of massive clumps associated with  $\text{H}_2\text{O}$  masers. But for all of these studies one has to be aware that maser amplification is strongly beamed, hence geometry dependent and therefore might not lead to a complete census of massive YSOs.

#### 3.2. Infrared selected surveys

An important step forward was the realization, that the Wood & Churchwell (1989) IRAS color criterion to select candidate UCHII regions will also lead to earlier stages if the sources have no association with free-free continuum observed in galaxy-wide cm surveys (Palla et al. 1991; Sridharan et al. 2002).

Although in subsequent deeper searches for free-free emission from HII regions a fraction of the selected sources was detected, a large amount of likely pre-UCHII regions objects could be identified and studied in more detail (Molinari et al. 1996; Beuther et al. 2002a,b). A similar approach, making use of the point source catalog from the MSX survey, was taken by Lumsden et al. (2002) and Hoare et al. (2004): they developed color criteria for the MSX observing bands to select a population of red MSX sources. An advantage over the IRAS selec-

tion is the higher angular resolution ( $18''$  vs.  $45 \times 240''^2$ ) and sensitivity of the MSX data.

But all of these searches probe already ongoing star formation and cannot (directly) identify an earlier cold precluster phase.

### 3.3. Cold dust surveys

Further progress was brought by the availability of sensitive bolometer arrays to probe the cold dust content of potential massive star forming regions.

As we have seen in the example of Fig. 1., usually many clumps can be found embedded in GMCs, which might contain massive star formation at very different stages. Therefore, one can search in the larger environs of objects found in the surveys described in the sections above for earlier, colder clumps. In the following, several of these surveys will be described in more detail.

A very prolific instrument was the SIMBA 1.2mm bolometer array (Nyman et al. 2001) operated at the SEST telescope: Hill et al. (2005) targeted a sample of 131 massive star forming regions selected from methanol maser and ultracompact HII region surveys which resulted in the detection of about 400 clumps. About one third of the clumps do not have a MIR detection with MSX, hence are promising examples of massive cold clumps in a stage before maser, bright IR sources and UCHII regions develop. Beltrán et al. (2006) observed with SIMBA the extension to the 4th Galactic quadrant of the IRAS color selected Palla/Molinari sample. In the 245 observed fields, 95 clumps without any MSX association were found. In both of these SIMBA surveys, the IR-quiet clumps are found to be less massive than the clumps with MSF association, but this result assumes the same temperatures for all of the clumps. Therefore the mass could still be similar if the IR-quiet clumps are much colder, which would be similar to the case of their lower mass prestellar siblings.

IRAS color selected regions with additional bright CS detections by Bronfman et al. (1996) were observed with SIMBA by Faúndez et al. (2004). An analysis of 4 massive cold clumps discovered in the survey was presented by Garay et al. (2004). Most of the fields targeted contain already UCHIIs, so that this survey covers many relatively high luminosity sources. This is similar to the approach of the SCAMPS survey (Thompson et al. 2005), which observed UCHIIs from Thompson et al. (2006) with evidence for secondary dust peaks in  $100''^2$  fields with SCUBA. Also in the fields targeted in the Beuther et al. (2002a) study of IRAS color selected, radioquiet objects (HMPOs), many cold, secondary clumps were found (Sridharan et al. 2005). Using MSX and IRAS flux density upper limits, they deduced luminosity upper limits of  $100 L_{\odot}$  for an average distance of 4 kpc.

A dust emission survey towards the outer Galaxy was conducted by Klein et al. (2005) towards a IRAS color selected sample. 128 massive dust clumps were detected and associated with NIR/MIR and Radio surveys to place them in a tentative evolutionary sequence from cold pre-cluster cores to star clusters that have already dispersed their parental clouds.

A promising hunting ground for massive cold cores are the infrared dark clouds discussed in Sect. 2.2.. Dust continuum surveys towards samples of IRDCs were conducted by Carey et al. (2000), Teyssier et al. (2002), and Rathborne et al. (2006), with the latter one covering the largest number of sources. Those

Table 1. Overview of recent dust continuum surveys. The last 2 columns give the total number of detected clumps and the number of clumps without association with either compact or diffuse MIR in the MSX survey, Note that for the latter, different surveys used slightly different criteria.

Survey	Bolometer	Size	RMS mJy/bm	N(tot)	N(noMSX)
Beuther et al. (2002a)	MAMBO	69x $\sim 20'^2$	10-15	154	56
Hill et al. (2006)	SIMBA	131x $\sim 60'^2$	100-150	404	112
Beltrán et al. (2006)	SIMBA	235x $\sim 100'^2$	25-40	615	95
Faúndez et al. (2004)	SIMBA	146x $\sim 150'^2$	40	321	n/a
Klein et al. (2005)	various	44x $\sim 10'^2$	3-400	126	23
Motte et al. (2007)	MAMBO	3 sq.deg.	20	129	93
Muñoz et al. (2007)	SIMBA	2 sq.deg.	25	347	n/a
Rathborne et al. (2006)	MAMBO	38x $\sim 36'^2$	10	188	140

mm/submm continuum surveys reveal a remarkable correlation between mid-IR absorption and optically thin dust emission. A fraction of the detected dust clumps is on a closer look associated with compact MIR sources, which is an indication of ongoing star formation even in the IRDCs (e.g. Pillai et al. 2006b).

### 3.4. Unbiased surveys for cold dust

A powerful tool for a complete census of massive clumps are unbiased surveys of either whole giant molecular cloud complex or even of the whole Galactic plane. Covering several square degrees, Motte et al. (2007) and Muñoz et al. (2007) measured the mm dust emission in the molecular complexes Cygnus X and NGC6357/NGC6334, respectively. The Cygnus X survey is described in detail in the contribution by Motte (this volume).

Several Galactic plane surveys are currently underway or planned. Results from the CSO/Bolocam 1.1mm survey are presented by Bally (this volume). ATLASGAL, the Galactic plane survey with the 850 $\mu$ m LABOCA bolometer camera at the APEX telescope, has finished its first coverage of the inner Galactic plane (Schuller et al., in prep.). These surveys reveal thousands of sources, many of them only detected at mm/submm wavelengths.

### 3.5. Summary

Recent and current dust continuum surveys produce new detections of a large numbers of cold massive clumps. A summary of some of the surveys discussed in the last sections is given in Table 1. Although the numbers of IR-quiet clumps are already impressive, very massive cold clumps which might turn into rich OB clusters are still rare. This is where the Galactic plane surveys are badly needed. The variety of selection criteria for the surveys yield sources in a variety of environs: e.g. with and without nearby powerful OB clusters and with locations ranging throughout the Galaxy. Some follow ups to determine their properties are already completed and will be discussed in the next section, but given the large amount of new data, several follow ups are still ongoing.

#### 4. Massive cold clump properties

The properties of the newly found massive cold clumps can be constrained with molecular line follow-up studies and continuum observations/data from other wavelengths. The latter can usually be extracted from available IR surveys, in particular to constrain the spectral energy distribution of the objects, whereas the line information needs dedicated observing campaigns. Some of the recent results will be summarized in this section.

##### 4.1. Physical conditions

Garay et al. (2004) analysed 4 IR-quiet clumps found in the Faúndez et al. (2004) survey. In addition to the dust continuum, also several CS transitions were observed. They found radii, masses and densities similar to clumps associated with IRAS and/or UCHII sources, but the temperatures limits they give for the IR-quiet clumps ( $<17$  K) are much lower. Two of the sources were covered also in the studies of Beuther et al. (2005) and Rathborne et al. (2005) which found evidence for ongoing star formation in the clumps. An interesting comparison between low- and high-mass clumps was done by Garay (2005) who found similar scaling relations  $\Delta v(R)$  and  $n(R)$  for the clumps but absolute values for the linewidths and densities considerably higher for the massive clumps. Pillai et al. (2006a) studied the temperature of clumps in IRDCs using ammonia and compared the results with similar studies towards HMPOs and UCHIIIs. They found linewidths and temperatures clearly smaller than for the more evolved objects, which is confirmed by the results from Sridharan et al. (2005). Detailed modeling of clumps in an IRDC towards W51 was done by Ormel et al. (2005). The submm continuum structure as well as the  $\text{HCO}^+$  excitation was included in the spherical models that also considered clumpiness and turbulence. The main finding is that for all three clumps evidence for heating and an increase of turbulence to the inside was found, even in the absence of indications for star formation from the infrared.

##### 4.2. Spectral energy distributions

Important information about the clumps can be extracted from their spectral energy distributions, most importantly the emerging luminosity. Instructive examples are given in Rathborne et al. (2005) and Beuther & Steinacker (2007), which demonstrate that the 24 and 70  $\mu\text{m}$  flux measurements that the Spitzer/MIPS instrument can provide are crucial for the determination of luminosities and the detection of a warmer component within the clumps. For large samples of sources, the results from the Spitzer/MIPSGAL survey of the Galactic plane have the potential to allow detailed studies of the SEDs of massive cold clumps and their luminosity function.

A promising method to reveal some of the coldest clumps is to make use of the ISOPHOT serendipity survey at 170  $\mu\text{m}$  and to cross-correlate it with the IRAS point source catalog to select sources that are considerably brighter at 170 than at 100  $\mu\text{m}$ . Birkmann et al. (2006) presented continuum and molecular line follow up observations of a clump found with this method and report temperatures of 12 K a mass of 280  $M_{\odot}$ , and spectra with signs for infall. Although these characteristics make the clump a very interesting candidate for a

cold precluster object, the data show also outflow wings, which provide even in this object evidence for already ongoing star formation.

### 4.3. Infall

Evidence for infall in the massive cold clump phase is still scarce and only a few observations of typical infall tracers have been published so far. The evidence for infall in the clump observed by Birkmann et al. (2006) was already mentioned, another source with such infall evidence is G25.38 studied by Wu et al. (2005) who derive an accretion rate of  $3.4 \times 10^{-3} M_{\odot}/\text{yr}$ , hence much higher than rates towards low mass Class 0 sources. But infall is certainly continuing to much later stages: Fuller et al. (2005) find for the Sridharan et al. (2002) sample of HMPOs accretion rates of  $0.2 - 1 \times 10^{-3} M_{\odot}/\text{yr}$  and Wu & Evans (2003) observed a clear excess of “blue” line profiles towards a subset of the Plume et al. (1997) water maser sample. The infall might still continue into the UCHII region phase as mid- $J$  CO line observations by Wyrowski et al. (2006a) indicate.

### 4.4. Chemical conditions

“Chemistry” is used here in a very broad sense, covering multi-line/-molecule observations of massive cold clumps and also depletion and deuteration studies. A variety of mm lines towards 43 IR dark clumps in the neighborhood of HMPOs is presented in Beuther & Sridharan (2007). Surprisingly, 18 sources have been clearly detected in SiO, in some cases with very broad line wings. The SiO emission is a strong indicator of shocks related to outflow activity from embedded young stellar objects. An even higher SiO detection rate towards clumps newly found in Cygnus X is reported by Motte et al. (2007), showing that star formation sets in very early on in the evolution of massive clumps. Other indications of early star formation activity in the Beuther & Sridharan (2007) study are an increase of turbulence to the denser inner parts of the clumps, measured by the increased line widths of line probes with higher critical densities, and methyl cyanide detections in 14% of the sample, which can be a signpost of embedded hot cores. The observed methanol abundance in the sample is close to the values found towards low mass clumps.

Since it is known from low mass clumps that in cold and dense gas depletion and deuterium fractionation should occur, first studies of CO depletion and deuterated molecules towards massive clumps have been performed. Fontani et al. (2006) find depletion and deuteration of  $N_2H^+$  towards IRAS selected HMPOs but the observations could not distinguish between cold, dense gas remnant from the HMPO formation or secondary colder clumps within the beam. Recent SMA interferometer follow ups of one of the sources show the  $N_2D^+$  in several condensations offset from the HMPO (see Fontani et al., this volume, and Fontani et al. 2007). Pillai et al. (2007) observed a sample of 32 massive clumps in IRDCs and the environs of UCHII regions. They find CO depletion factors of  $\sim 5$  and detected deuterated ammonia in 23 sources, including some of the highest degrees of deuteration for ammonia reported so far with values for  $[NH_2D]/[NH_3]$  up to 0.6. No trend of depletion or deuteration with the temperature measured using ammonia was found, which could be an effect of the relatively large distances to the massive clumps compared to their lower mass



siblings, so that the gas morphology in the beams is much more complex. These high deuteration fractions confirm the early evolutionary stage of the clumps.

#### 4.5. Summary

Massive cold clumps have higher masses and densities in comparison to their lower mass cousins. Infall seem to start at this stage but observations indicate that it continues also through later stages. Molecular line studies provide evidence for depletion and, for some sources, deuteration as high as in low mass prestellar clumps. A wide range of star formation activity is still hiding in the clumps and need to be followed up with high angular resolution studies, which are described in the next section.

### 5. Cores in IR-quiet clumps

With the help of powerful interferometers in the cm–submm wavelengths range, it is now possible to probe the small scale structure within the IR-quiet clumps discussed in the last section.

Wang et al. (2007) present a high resolution study (with 0.1 pc beamsize) of the IRDC G28.34+0.06 with the VLA in ammonia: the northern part of the IRDC harbors already a very active region of star formation with a luminosity of  $10^4 L_{\odot}$ , water maser, broad lines and ammonia temperatures above 30 K. The quiescent cores hide in the filamentary southern part of the IRDC with temperatures below 20 K and smaller linewidths. The cores in the southern part show a clear trend of temperature decrease to their inner high column density parts.

The PdB interferometer has been used by Rathborne et al. (2007) to image four clumps in IRDCs, which break up into 12 cores. More details are given in the contribution by Jackson (this volume). With the high PdBI sensitivity, in one of the cores the “line forest” signature of a hot molecular core was found, which represents an important link between the early stages of star formation in IRDCs and the later hot core/UCHII phases. Another PdBI study of a clump in an IRDC is presented in Beuther et al. (2005). The main core in the clump has a mass of  $180 M_{\odot}$ .  $4.5\mu\text{m}$  Spitzer emission, which is known to be strong towards molecular outflows, is emanating from the core, indicating the presence of a collimated flow from a young stellar object embedded in the core. This is supported by the high resolution molecular data that shows the turbulent linewidths contribution increasing to the center.

Yet another high resolution view on a cold, massive clump is given by Wyrowski et al. (2006b, 2007). Close to the extremely line rich hot molecular core G327.3–0.6, a massive clump seen in absorption in the MIR is located. ATCA and APEX observations of  $\text{N}_2\text{H}^+$  constrain the physical conditions in the clump to temperatures of 20 K and densities in excess of  $5 \times 10^6 \text{ cm}^{-3}$ . With the high angular resolution provided by ATCA, the clump breaks up into many cores with sizes of 0.1–0.2 pc. Only one of them is associated with a very red Spitzer/GLIMPSE source. The virial mass of the cores is much smaller than the mass derived from their densities and sizes, hence the objects might be candidates for massive protocluster in the process of making, unless collapse is prevented by other means, e.g. magnetic fields.

## 6. Conclusions and outlook

With a growing number of large scale cold dust emission surveys, used in combination with IR surveys of the Galactic plane, this is a very prolific time for the identification of precluster clump candidates. The properties of clumps are fairly well known now from the follow-up studies towards the newly found sources. Still, there are many cases, where star formation activity can be found associated with the clump or the embedded cores on a closer look. On one hand, this shows that these clumps indeed started to turn into (massive) stars, hence have led us to initial conditions of massive star formation, on the other hand it means that pure “starless” objects are still rare, objects that are yet unaltered by the influence of the star formation process.

For better statistics, unbiased large scale surveys are on the way in a variety of wavebands: submillimeter bolometer surveys are imaging the whole Galactic plane, Spitzer provides a spectacular view onto our Milky Way in the mid-infrared, and the Herschel Space Observatory in the not so far future will help to put stronger constraints even on the far-infrared part, where the SEDs of massive cold clumps peak. Continuing progress on the interferometer side, culminating with the advent of the eVLA and ALMA, will allow new high resolutions views of the properties of the cores out of which massive clusters will form.

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